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Optically induced spin polarization of an electric current through a quantum dot

Anatoly Yu. Smirnov*
D-Wave Systems Inc., 320-1985 West Broadway, Vancouver, British Columbia, Canada, V6J 4Y3

Lev G. Mourokh†
Department of Physics and Engineering Physics, Stevens Institute of Technology, Hoboken, New Jersey 07030, USA

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We examine a feasibility of the spin polarization of the electron current through a semiconductor quantum dot subject to a continuous circularly polarized optical irradiation resonant to the electron-heavy hole transition. Electrons having a certain spin polarization experience Rabi oscillation and their energy levels are shifted by the Rabi frequency. Correspondingly, the equilibrium chemical potential of the leads and the lead-to-lead bias voltage can be adjusted so only electrons with spin-up polarization or only electrons with spin-down polarization contribute to the current. The temperature dependence of the spin polarization of the current is also discussed.

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Recently, spin electronics, so-called *spintronics*, has become a focal point of intense research interest (see, for example, Ref. 1 and references therein). Electronic devices employing the additional spin-degree of freedom, as well as purely spin-based devices, can increase the speed of performance, consume less power, and provide novel modes of operation in comparison with conventional counterparts. Creation, control, and transmission of spin polarization constitute the principal tasks of spintronics. To polarize electron and nuclear spins, one can apply, for example, an external magnetic field (or put spin particles in contact with ferromagnetic materials).[2,3] Other possibilities for the creation of the spin polarization include optical orientation of electron spins by a circularly polarized light[4] and polarized spin injection from the ferromagnetic-normal semiconductor junction.[5]

In the present paper we propose to combine the optical spin polarization technique with electron transport through semiconductor quantum dots to produce a spin polarization of the electron current. Electron spin polarization in the dot can be achieved by the circular polarized light. In particular, the photons with the positive helicity create heavy holes with spin $3/2$ and electrons with spin $-1/2$, whereas the photons having negative helicity create heavy holes with spin $-3/2$ and electrons with spin $1/2$. For the self-assembled quantum dots (for example, InGaAs/GaAs), the lattice mismatch leads to the removal of the degeneracy between heavy and light hole energy levels, and the electron-heavy hole pairs can be created resonantly. This is an advantage over the usual optically induced polarization because the efficiency of polarization increases without the light holes involved. Under resonant continuous optical irradiation, electron-hole pairs (with certain electron spin projections) exhibit Rabi oscillations,[6] and the energy level for the electrons having this spin projection is shifted by $\pm\Omega_R$, where Ω_R is the Rabi frequency. We show that in this case the conductance peaks occur not when the chemical potential of the leads is in the resonance with the energy of the quantum dot level, E_c, but when it is in the resonance with the energy $E_c\pm\Omega_R$ ($\hbar=1$). However, for electrons having the spin projection that is not affected by the light, the conductance peak position remains the same. Accordingly, for appropriate values of the Rabi frequency, the equilibrium chemical potential of the leads, and the lead-to-lead voltage bias, the spin polarization of the electron current through the quantum dot can be achieved, and, moreover, the direction of the polarization can be controlled by these parameters.

We examine a self-assembled InGaAs/GaAs semiconductor quantum dot that is electrically coupled to two leads (a similar structure was examined experimentally, for example, in Ref. 7) and is subject to a continuous circularly polarized light having frequency resonant to the electron-heavy hole transition and negative helicity. In this case, photons create electron-hole pairs in the dot with electrons and holes having definite spin projections, $1/2$ and $-3/2$, respectively. Electrons with both spin projections can tunnel from the leads to the dot with spin-independent tunneling rates, whereas the hole tunneling is assumed to be suppressed.

The Hamiltonian of the system has the form

$$H = E_c(a_1^+a_1 + a_2^+a_2) + E_v d^+d + \sum_{\alpha,k,\sigma} E_{\alpha k} c^+_{\alpha k,\sigma} c_{\alpha k,\sigma} - F(t)(a_1^+d^+ + da_1) - \sum_{\alpha,k,\sigma}(T_{\alpha k}c^+_{\alpha k,\sigma}a_\sigma + T^*_{\alpha k}a^+_\sigma c_{\alpha k,\sigma}), \quad (1)$$

with $\alpha=L$, R and the spin index $\sigma=1,2$. Operators $c_{\alpha k,\sigma}$ are related to electrons in leads, whereas a_1, a_2 describe an electron in the dot with spin projections $\pm 1/2$ as $a_1=a_{1/2}$ and $a_2=a_{-1/2}$. The holes have only one projection, so that $d=d_{-3/2}$. The monochromatic electromagnetic field is given by $F(t)=Fe^{i\omega_0 t}+F^*e^{-i\omega_0 t}$. The Coulomb interaction is taken into account in the sense of the Coulomb blockade, so the total charge of particles in the dot cannot exceed one electron charge. In this, the electron-hole pair may not have any charge and the peculiarities associated with the different space distribution of the electron and hole wave functions are neglected. From this Hamiltonian we derive the equations of motion for the electron-hole amplitudes as

$$i\dot{a}_1 = E_c a_1 - F(t) d^+ - \sum_{\alpha,k} T^*_{\alpha k} c_{\alpha k,1}, \tag{2a}$$

$$i\dot{a}_2 = E_c a_2 - \sum_{\alpha,k} T^*_{\alpha k} c_{\alpha k,2}, \tag{2b}$$

$$i\dot{d}^+ = - E_v d^+ - F(t) a_1, \tag{2c}$$

and

$$i\dot{c}_{\alpha k,\sigma} = E_{\alpha k} c_{\alpha k,\sigma} - T_{\alpha k} a_\sigma. \tag{2d}$$

Introducing new electron-hole variables, $A_\sigma = a_\sigma e^{iE_c t}$ and $D = de^{iE_v t}$, we rewrite Eq. (2) as

$$i\dot{A}_1 = F(t) e^{i(E_c+E_v)t} D^+ - \sum_{\alpha,k} T^*_{\alpha k} e^{iE_c t} c_{\alpha k,1}, \tag{3a}$$

$$i\dot{A}_2 = - \sum_{\alpha,k} T^*_{\alpha k} e^{iE_c t} c_{\alpha k,2}, \tag{3b}$$

$$i\dot{D}^+ = - F(t) e^{-i(E_c+E_v)t} A_1, \tag{3c}$$

and

$$i\dot{c}_{\alpha k,\sigma} = E_{\alpha k} c_{\alpha k,\sigma} - T_{\alpha k} e^{-iE_c t} A_\sigma. \tag{3d}$$

For the resonant electromagnetic field with the frequency $\omega_0 = E_c + E_v$, the rotating wave approximation (RWA) can be applied and, accordingly, $F(t) e^{i(E_c+E_v)t} \simeq F^*, F(t) e^{-i(E_c+E_v)t} \simeq F$. Correspondingly, the equation for the amplitude A_1 has the form

$$\left[\left(i\frac{d}{dt} \right)^2 - |F|^2 \right] A_1 = - i\frac{d}{dt} \sum_{\alpha k} T^*_{\alpha k} e^{iE_c t} c_{\alpha k,1}, \tag{4}$$

where the amplitude of the electromagnetic field, $|F|$, denotes the Rabi frequency: $\Omega_R = |F|$. The response of the leads is described by the relation[8]

$$c_{\alpha k,\sigma}(t) = c^{(0)}_{\alpha k,\sigma}(t) - T_{\alpha k} \int dt_1 g^r_{\alpha k}(t,t_1) e^{-iE_c t_1} A_\sigma(t_1), \tag{5}$$

where

$$g^r_{k\alpha}(t,t_1) = - ie^{-iE_{k\alpha}(t-t_1)} \theta(t-t_1) \tag{6a}$$

and

$$\langle c^{(0)}_{k\alpha,\sigma}(t_1)^+ c^{(0)}_{k\alpha,\sigma}(t) \rangle = f_\alpha(E_{k\alpha}) e^{-iE_{k\alpha}(t-t_1)} \tag{6b}$$

are the Green functions of electrons in the leads, $\theta(t-t_1)$ is the unit Heaviside function, and $f_\alpha(E) = \{\exp[(E-\mu_\alpha)/T] + 1\}^{-1}$ is the Fermi distribution with temperature T. Here, $\mu_L = \mu + eV/2$ and $\mu_R = \mu - eV/2$, where μ is the equilibrium chemical potential of the leads and V is the voltage bias applied to the leads.

Substituting Eq. (5) into Eq. (4), we obtain

$$\left[\left(i\frac{d}{dt} \right)^2 - \Omega_R^2 \right] A_1 - i\frac{d}{dt} \sum_{\alpha,k} |T_{\alpha k}|^2 \int dt_1 g^r_{\alpha k}(t,t_1) e^{iE_c(t-t_1)} A_1(t_1)$$
$$= - i\frac{d}{dt} \sum_{\alpha,k} T^*_{\alpha k} e^{iE_c t} c^{(0)}_{\alpha k,1}. \tag{7}$$

The solution of this equation can be written as

$$A_1(t) = - i\frac{d}{dt} \int dt' G^r_1(t-t') \sum_{\alpha,k} T^*_{\alpha k} e^{iE_c t'} c^{(0)}_{\alpha k,1}(t'), \tag{8}$$

where the Fourier transform of the retarded Green function $G^r_1(t-t')$ is given by

$$G^r_1(\omega) = \frac{1}{\omega^2 - \Omega_R^2 - \omega \sum_{\alpha,k} |T_{\alpha k}|^2 g^r_{\alpha k}(\omega + E_c)}, \tag{9}$$

with $g^r_{\alpha k}(\omega) = 1/(\omega - E_{\alpha k}) - i\pi\delta(\omega - E_{\alpha k})$. Broadenings of the electron level in the dot due to its connection to the leads is described by the damping coefficients $\Gamma_\alpha(\omega) = 2\pi\Sigma_k |T_{k\alpha}|^2 \delta(\omega - E_{k\alpha})$, whereas the real part of the function $g^r_{\alpha k}(\omega + E_c)$ produces insignificant corrections to the Rabi frequency Ω_R. With a notation for the average linewidth of the electron level, $\Gamma(\omega) = (1/2)[\Gamma_L(\omega) + \Gamma_R(\omega)]$, we obtain the expression for the Green function $G^r_1(\omega)$ as

$$G^r_1(\omega) = \frac{1}{\omega^2 - \Omega_R^2 + i\omega\Gamma(\omega + E_c)}. \tag{10}$$

The electron current through the quantum dot is given by

$$I_{\alpha,\sigma} = \frac{d}{dt} \sum_k \langle c^+_{\alpha k,\sigma}(t) c_{\alpha k,\sigma}(t) \rangle = i \sum_k T_{\alpha k} e^{-iE_c t} \langle c^+_{\alpha k,\sigma} A_\sigma \rangle + \text{H.c.} \tag{11}$$

It should be noted that the total current has two components, I_1 with spin projection $+1/2$ and I_2 with spin projection $-1/2$. Substituting Eq. (5) into Eq. (11), we obtain

$$I_{\alpha,\sigma} = i \sum_k T_{\alpha k} e^{-iE_c t} \langle (c^{(0)}_{\alpha k,\sigma})^+ A_\sigma \rangle$$
$$- i \sum_k |T_{\alpha k}|^2 \int dt' [g^r_{\alpha k}(t,t')]^+ e^{-iE_c(t-t')} \langle A_\sigma(t')^+ A_\sigma(t) \rangle$$
$$+ \text{H.c.} \tag{12}$$

The first term in the right-hand side of Eq. (12) for the spin-up polarized current ($\sigma = 1$) can be evaluated as

$$i \sum_k T_{\alpha k} e^{-iE_c t} \langle (c^{(0)}_{\alpha k,1})^+ A_1 \rangle + \text{H.c.}$$
$$= 2 \int \frac{d\omega}{2\pi} (\omega - E_c) \text{Im}[G^r_1(\omega - E_c)] f_\alpha(\omega) \Gamma_\alpha(\omega). \tag{13}$$

It follows from Eq. (8) that the correlator $\langle A_1(t')^+ A_1(t) \rangle$ has the form $(\alpha, \beta = L, R)$

$$\langle A_1(t')^+A_1(t)\rangle = \int \frac{d\omega}{2\pi} e^{-i\omega(t-t')}\omega^2|G_1^r(\omega)|^2\sum_\beta \Gamma_\beta(\omega+E_c)f_\beta(\omega + E_c), \quad (14)$$

and, consequently, the second term of the right-hand side of Eq. (12) for the spin-up polarized current can be written as

$$-i\sum_k |T_{\alpha k}|^2 \int dt'[g^r_{\alpha k}(t,t')]^+ e^{-iE_c(t-t')}\langle A_1(t')^+A_1(t)\rangle + \text{H.c.}$$

$$= \int \frac{d\omega}{2\pi}(\omega - E_c)^2|G_1^r(\omega-E_c)|^2\sum_\beta \Gamma_\alpha(\omega)\Gamma_\beta(\omega)f_\beta(\omega). \quad (15)$$

The total spin-up polarized current, $I_{\alpha,1}$ is equal to the sum of the terms, Eqs. (13) and (15), and for the steady-state regime, the current carrying the spin $+1/2$ has the form

$$I_1 = I_{L,1} = -I_{R,1} = \int \frac{d\omega}{2\pi}\frac{(\omega-E_c)^2[f_L(\omega)-f_R(\omega)]}{[(\omega-E_c)^2-\Omega_R^2]^2+[(\omega-E_c)\Gamma(\omega)]^2}\Gamma_L(\omega)\Gamma_R(\omega). \quad (16)$$

The current with the spin polarization $-1/2$ (which is not affected by the optical irradiation) can be determined using the same procedure as

$$I_2 = \int \frac{d\omega}{2\pi}\frac{[f_L(\omega)-f_R(\omega)]}{(\omega-E_c)^2+\Gamma^2(\omega)}\Gamma_L(\omega)\Gamma_R(\omega). \quad (17)$$

Components of a zero-temperature conductance of the system, $G_{\pm 1/2}=(d/dV)(eI_{1,2})$, related to the different spin projections, exhibit the resonant behavior as functions of the equilibrium chemical potential of the leads, μ, (or the gate voltage applied to the dot) as

$$G_{+1/2} = \frac{e^2}{h}\frac{(\mu-E_c)^2\Gamma^2}{[(\mu-E_c)^2-\Omega_R^2]^2+(\mu-E_c)^2\Gamma^2}, \quad (18)$$

$$G_{-1/2} = \frac{e^2}{h}\frac{\Gamma^2}{(\mu-E_c)^2+\Gamma^2}, \quad (19)$$

where we assume symmetric coupling to the leads with $\Gamma = \Gamma_{L/R} = \Gamma_{L/R}(\omega=\mu)$. This resonant behavior is illustrated by Fig. 1 for the Rabi frequency $\Omega_R=10\Gamma$. One can see from this figure that the conductance peaks for the electrons having spin projection $1/2$ (affected by the optical irradiation) are shifted from the equilibrium resonant condition ($\mu=E_c$) by $\pm\Omega_R$. Furthermore, it is evident that with variation such parameters as the equilibrium chemical potential of the leads, the Rabi frequency, and the lead-to-lead voltage bias, regimes with different spin polarization of the current through the quantum dot can be achieved.

To describe the spin polarization of the current and its dependence on the system parameters, we introduce the polarization coefficient as

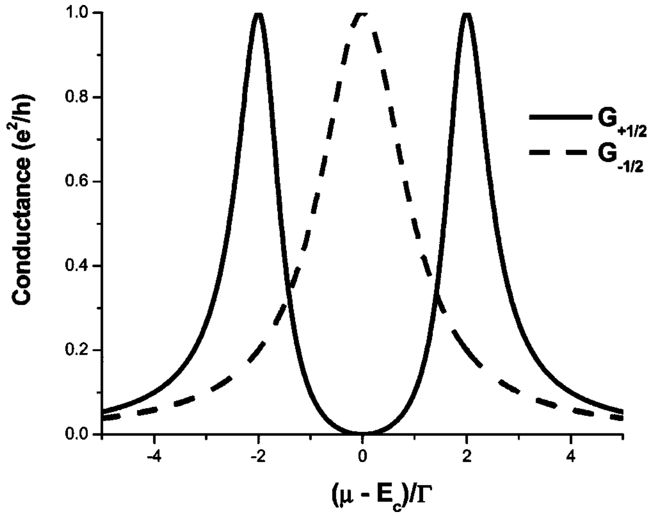

FIG. 1. Zero-temperature conductances for the electrons having different spin projections as a function of the equilibrium chemical potential of the leads for $\Omega_R=10\Gamma$.

$$P = \frac{I_1 - I_2}{I_1 + I_2}. \quad (20)$$

The lead-to-lead voltage dependencies of the total current and the polarization coefficient are shown in Fig. 2 for $\mu - E_c = 5\Gamma$, $\Omega_R=20\Gamma$, and $T=0.43\Gamma$. It is evident from this figure that there are several steps in the current-voltage characteristics. The first one occurs when the chemical potential of the right lead, $\mu_R=\mu-eV/2$, passes through the electron level with the energy E_c and this level becomes conductive. The electrons in this level have spin projection $-1/2$ and the current is strongly polarized. The second step corresponds to the voltage at which the chemical potential of the left lead, $\mu_L=\mu+eV/2$, passes through the electron level with the energy $E_c+\Omega_R$ and electrons from this level having spin projection $+1/2$ start to contribute to the current. Accordingly, current becomes only partially polarized. Finally, the third

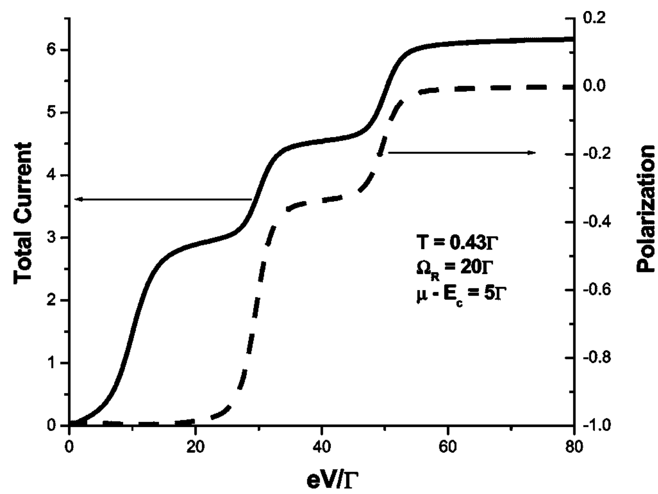

FIG. 2. The total current and the current polarization as functions of the applied lead-to-lead bias.

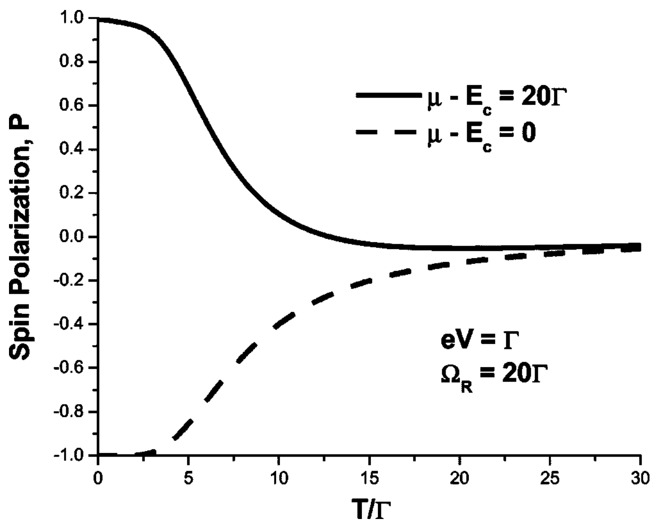

FIG. 3. Temperature dependence of the current polarization.

step occurs when the chemical potential of the right lead passes through the electron level with the energy $E_c - \Omega_R$ and the spin polarization of the current is fully compensated.

The temperature dependence of the polarization coefficient is presented in Fig. 3 for small applied lead-to-lead bias and two values of the equilibrium chemical potential of the leads associated with the resonances with electron levels having different spin polarization. One can see in this figure that at temperatures comparable to the Rabi frequency, the spin polarization of the current vanishes. Moreover, at such relatively high temperature other mechanisms of decoherence (electron-phonon interaction, in particular) come to play a significant role; therefore, to preserve the spin polarization, temperature should be kept low enough.

Finally, we consider the conditions necessary to observe the calculated effects in experiment. If we assume the lead-dot coupling constant to be $\Gamma = 20\ \mu eV$, then, $\Omega_R = 20\Gamma = 400\ \mu eV$, which corresponds to the excitation density of $350\ \mathrm{kW/cm^2}$, and temperature used for Fig. 2 is $T = 0.43\Gamma = 100$ mK.

In conclusion, we have shown that the spin polarization of the electron current through the quantum dot can be achieved in a controllable way, if the dot is irradiated continuously by the resonant circularly polarized light. In this case, electron-hole pairs with electrons having certain spin polarization experience Rabi oscillations and the energetic level of these electrons is shifted by $\pm\Omega_R$. With an appropriate choice of the equilibrium chemical potential of the leads and the lead-to-lead bias voltage, the current through the dot is spin polarized and the direction of this polarization can be manipulated. We have also shown that at low temperature the degree of polarization can be very high (up to 100%). It should be emphasized that the corresponding experimental studies can be carried out with existing technology.

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*Electronic address: anatoly@dwavesys.com

†Electronic address: lmurokh@stevens.edu

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